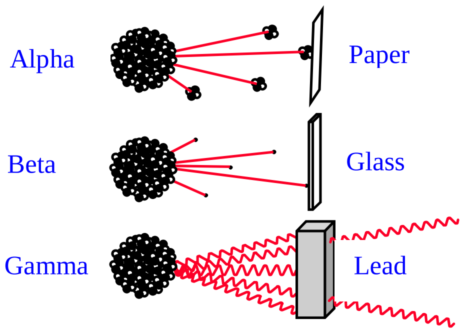
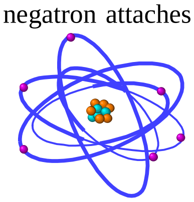
Ionizing Radiation

What Is It? Ionizing radiation is energy that is carried by any of several types of particles and rays (electromagnetic radiation) given off by radioactive material, X-ray machines, and nuclear reactions. This energy can knock electrons out of molecules with which they interact, thus creating ions. Non-ionizing radiation, such as that emitted by a laser, is different because it does not create ions when it interacts with matter but dissipates energy generally in the form of heat. The three main types of ionizing radiation are alpha particles, beta particles, and gamma rays.



An alpha particle consists of two protons and two neutrons and is identical to the nucleus of a helium atom. Because of its relatively large mass and charge, an alpha particle produces ions in a very localized area. An alpha particle loses some of its energy each time it produces an ion (its positive charge pulls electrons away from atoms in its path), finally acquiring two electrons from an atom at the end of its path to become a complete helium atom. An alpha particle has a short range (several centimeters) in air and cannot penetrate the outer dead layer of skin.

Beta particles can be either negative (negatron) or positive (positron). Negatrons are identical to electrons and originate in the nucleus of an atom that undergoes radioactive decay by changing a neutron into a proton. The only difference between a negative beta particle (negatron) and an electron is the ancestry. A beta particle originates in the nucleus whereas an electron is external to the nucleus. Unless otherwise specified, the term "beta particle" generally refers to a negatron. A positron is emitted from an atom that decays by changing a proton into a neutron. Beta particles are smaller and more penetrating than alpha particles, but their range in tissue is still quite limited. When its energy is spent, a negatron attaches itself to an atom and becomes an ordinary electron, while a positron collides with an ambient electron and the two particles annihilate each other, producing two gamma rays. When a negatron passes close to the nucleus of an atom, the strong attractive coulomb force causes the beta particle to deviate sharply and lose energy at a rate proportional to the square of the acceleration. This energy manifests itself as photons termed Bremsstrahlung. The amount of beta energy converted into photons is directly proportional to the energy of the beta particle. This effect is only significant for high-energy beta particles generally passing through very dense materials such as lead, i.e., those with higher atomic numbers and so more protons in the nucleus.



Gamma rays are electromagnetic radiation given off by an atom as a means of releasing excess energy. They are bundles (quanta) of energy that have no charge or mass and can travel long distances through air (up to several hundred meters), body tissue, and other materials. A gamma ray can pass through a body without hitting anything, or it may hit an atom and give that atom all or part of its energy. This normally knocks an electron out of the atom, ionizing it. This electron then uses the energy it receives from the gamma ray to create additional ions by knocking electrons out of other atoms. Because a gamma ray is pure energy, it no longer exists once it loses all its energy. The capability of a gamma ray to do damage is a function of its energy, where the distance between ionizing events is large on the scale of the nucleus of a cell.

Additional forms of ionizing radiation beyond the three types shown in the figure above include neutrons, protons, neutrinos, muons, pions, heavy charged particles, X-rays and others. Essentially all radioactive materials at the Hanford Site originated from neutron interactions with uranium fuel to produce plutonium. Byproducts of this process include fission products (most of which are in the high-level waste currently in on-site storage), activation products in the containment and reactor coolant materials, and various radioactive wastes. However, the radioactive hazards that remain at the Hanford Site are largely those associated with the three general types of radiation shown above, so the discussion here is limited to these three.

Where Does It Come From? All organisms are being exposed to ionizing radiation from natural sources all the time. Radiation doses are typically given in units of rem – an acronym for Roentgen equivalent man – or millirem (mrem), which is one one-thousandth of a rem. This unit was developed to allow for the consistent reporting of hazards associated with the various types and energies of radiation on the human body. The rem is the product of the absorbed dose in rads (i.e., the amount of energy imparted to tissue by the radiation, where 1 rad equals 0.01 joules/kg) and factors for the relative biological effectiveness (RBE) of the radiation. The RBE is directly related to the linear energy transfer (LET) or distance over which the radiation energy is imparted to the absorbing medium and is accounted for by a quality factor. For example, alpha particles are 20 times more hazardous than beta particles for the same energy deposition and hence have a quality factor of 20, whereas the quality factor for beta particles is one. The International Commission on Radiological Protection (ICRP) has developed a methodology for reporting the effective dose equivalent. This is the product of the dose (in rem or mrem) to individual tissues and the tissue-specific weighting factors (fractional values less than one) that indicate the relative risk of cancer induction or hereditary defects from irradiation of that tissue, summed over all relevant tissues. By use of the effective dose equivalent, it is possible to compare the relative radiation hazards from various types of radiation that impact different organs of the body. The doses discussed below are effective dose equivalents.

More than 80% of the total dose received by individuals in the United States comes from natural sources; 55% comes from radon gas decay products, 8% from cosmic radiation, 8% from terrestrial radiation, and 11% from internal sources such as potassium-40. The rest comes from man-made sources that include medical X-rays (11%), nuclear medicine (4%), consumer products (3%), radioactive fallout, and nuclear power plants (<1%). These percentages are representative, and not all people are exposed to the same sources to the same degree. The National Council on Radiation Protection and Measurements estimates an average radiation dose of 360 mrem/yr from natural and man-made sources, with about 300 mrem/yr from natural sources and 60 mrem/yr from man-made sources (mostly for medical procedures). For reference, a person receives a dose of about 5 mrem on a flight from New York City to Los Angeles, and a typical chest X-ray produces a dose of about 10 mrem.

How Is It Used? Radioactive materials and other sources of ionizing radiation are widely used to diagnose and treat diseases in human and veterinary medicine. Medical and dental X-rays are used to detect problems such as broken bones and dental cavities. Sealed radiation sources are used to deliver very high, localized radiation doses to treat certain types of cancers. Ionizing radiation also has a number of industrial and commercial uses. Radioactive sources are used in consumer products such as smoke detectors and to sterilize food products. Ionizing radiation is also used to test materials, inspect welds, generate heat and electricity for space travel, determine soil moisture content, and track the movement of various elements in the environment and human body (through use of radioactive tracers). Additional uses continue to be identified.

What's in the Environment? Exposure to background radiation and naturally occurring radioactive materials results in an annual dose of about 300 mrem/yr. Of this total, about one-third is due to external ionizing radiation, the main contributors being cosmic rays and terrestrial gamma rays (29 mrem/yr each), and radionuclides within the body (40 mrem/yr). Cosmic rays are produced when subatomic particles originating outside the solar system interact with particles in the upper atmosphere to produce gamma rays, neutrons and leptons that can reach and penetrate the earth's surface. It is these secondary particles and rays that produce the dose from cosmic radiation. Naturally occurring radioactive elements such as uranium, thorium and radium are present in soil, rock, water, and all other environmental media, and certain of these radionuclides (and their radioactive decay products) give off gamma rays as they undergo radioactive decay. The principal contributor to the dose from radionuclides in the body is potassium-40, which decays by emitting an energetic beta particle and gamma rays. About two-thirds of the background radiation dose (of 300 mrem/yr) is due to intake of radionuclides into the body. The largest contributor is inhalation of radon-220 and radon-222 gases and their short-lived radioactive decay products, which are charged particles that readily attach to airborne dust particles. In fact, inhalation of radon gas contributes nearly all of the 200 mrem/yr attributable to radionuclide intake, and most is due to the short-lived radon decay products polonium-218 and polonium-214. Ingestion of food and water containing naturally occurring radionuclides accounts for only a few mrem/yr.

What Are the Primary Health Effects? High doses of ionizing radiation can lead to effects such as skin burns, hair loss, birth defects, illness, cancer, and death, depending on the dose and the period of time over which it is received. Acute doses (such as from a serious accident involving nuclear materials) can result in damage to the blood-forming organs, gastrointestinal tract, and central nervous system. Very high doses, e.g., on the order of 500 rem (or 500,000 mrem) or more, can cause death in many (but not all) individuals, depending on the degree of medical intervention. The main health concern associated with radiation exposure is the induction of various cancers. Additional effects may include genetic mutations (although none have been observed in humans) and teratogenic effects such as mental retardation. The U.S. Environmental Protection Agency (EPA) has indicated that for radioactively contaminated Superfund sites, the risk from cancer is limiting and should be used as the sole basis for assessing radiation-related human health risks. The EPA noted that on average, about 50% of all cancers that can be induced by radiation (they can also be caused by other agents) are fatal, ranging from about 10% for thyroid cancer to 100% for liver cancer. Other EPA estimates for specific isotopes indicate the average may be higher, e.g., 60 to 70% or more.

What Happens to It in the Body? Radioactive materials can enter the body by inhalation, ingestion, or dermal absorption. In addition, gamma radiation external to the body can penetrate the skin and produce a dose in various tissues. Inhalation is the primary exposure mode for gaseous radionuclides (such as radon), and particulates near the source of an airborne release. A fractional amount of inhaled radionuclides is transferred from the lungs to the blood, where it distributes to other organs. The extent of absorption is strongly dependent on the radionuclide and its chemical form. Ingestion is the primary uptake mode for radionuclides in soil, water, and food, including those naturally occurring (such as radium and uranium in soil and groundwater) and man-made (such as plutonium from radioactive fallout). A fractional amount of ingested radionuclides is absorbed from the gastrointestinal tract into the blood while the rest clears the body through normal biological processes via urine and feces. As with inhalation, the extent of uptake depends on the radionuclide and its chemical form. The skin is generally an effective barrier against absorption of radionuclides, so dermal absorption is a very minor route of exposure. An exception to this is dermal absorption of tritiated water, i.e., water containing some amount of tritium (hydrogen-3) in place of a normal hydrogen atom in the water molecule, which is absorbed through the skin in the same manner as ordinary water.

What Is the Risk? While the EPA has developed lifetime cancer mortality risk coefficients for nearly all radionuclides, the agency has not developed a risk coefficient for ionizing radiation as a general category. A nominal mortality value of 5×10^{-7} incremental cancer risk per mrem has been identified for low-LET radiation delivered at a low dose and dose rate.